Small-x Physics in PHENIX

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d+Au Physics in PHENIX

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Workshop on Early Physic with Heavy Ion Collisions @ LHC

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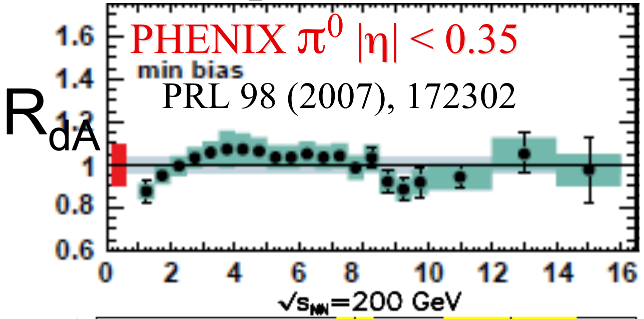
Outline:

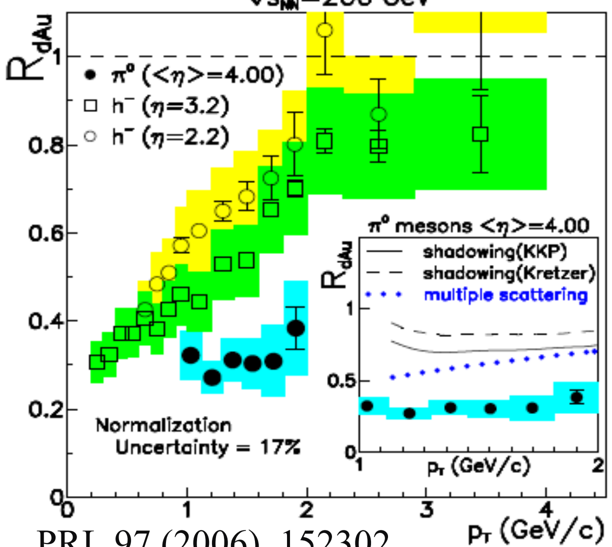
- Introduction
- Hadron-pair measurements in d+Au in PHENIX
- Results
  - Small-x: mid-forward correlations
  - Very(!) small-x: forward-forward correlations
- Discussion
- Summary

** PhD thesis work of Beau Meredith, U Illinois
http://arxiv.org/abs/1105.5112

Nuclear Modification in d+Au

- The d+Au measurements at RHIC have served as the reference system to investigate Cold Nuclear Matter effects.
  - Observe little or no modification at mid-rapidity, but significant suppression with increasing rapidity (decreasing parton fraction x).
  - Explanations: Shadowing, initial energy loss, gluon saturation,…



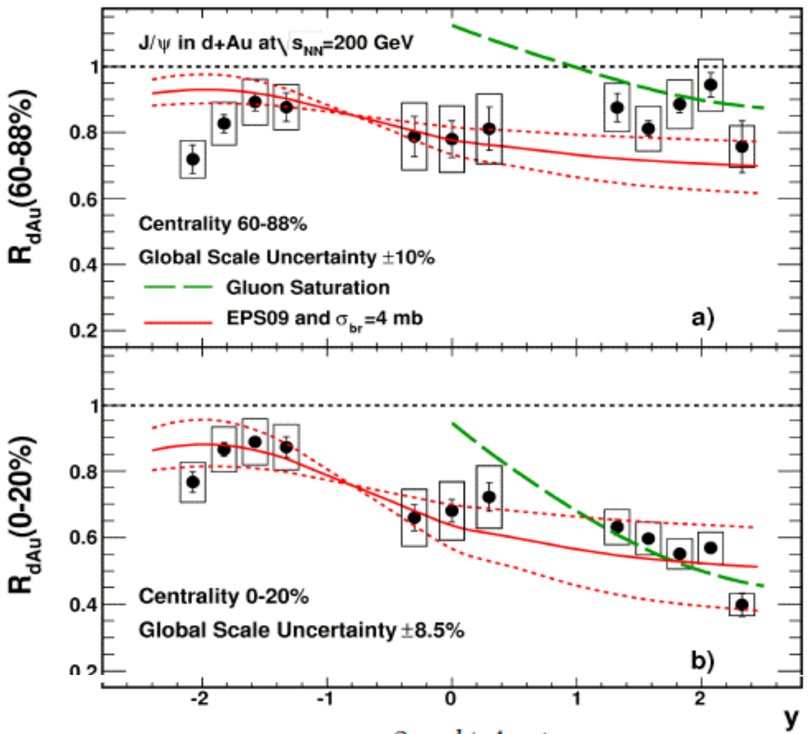


PRL 97 (2006), 152302

BRAHMS, h- η=3.2

STAR π^0 η= 4

PHENIX J/ψ

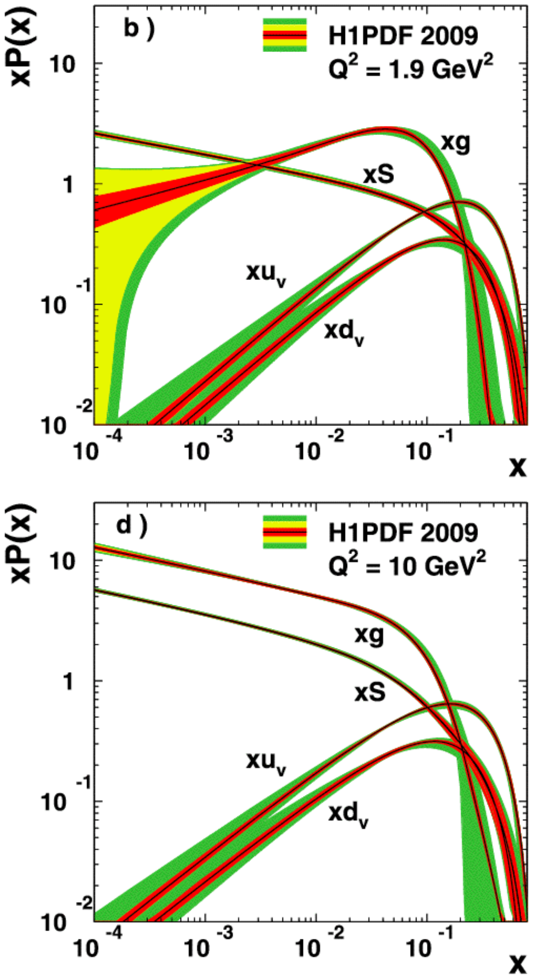


$$R_{dAu} \equiv \frac{1}{\langle N_{coll}\rangle} \frac{d^2N^{d+Au}/dp_T d\eta}{d^2N^{p+p}_{inel}/dp_T d\eta}$$

Nuclear Shadowing

PHENIX

Proton Parton Distribution Functions
PDFs (from fits to ep@HERA)



Nuclear PDF ≠ proton PDF

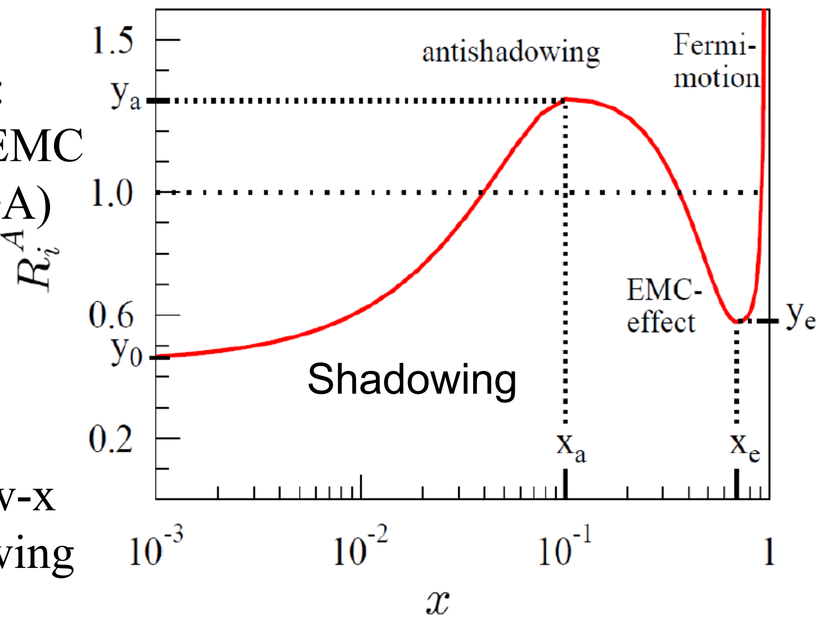
Extract nPDFs by fit to data on nuclei: e.g. SLAC, NMC, EMC DIS+DY+RHIC(d+A)

Gluons dominate low-x region where shadowing is significant.

F.D. Aaron et al, [H1 Collaboration] Eur. Phys. J. C 64, 561 (2009)

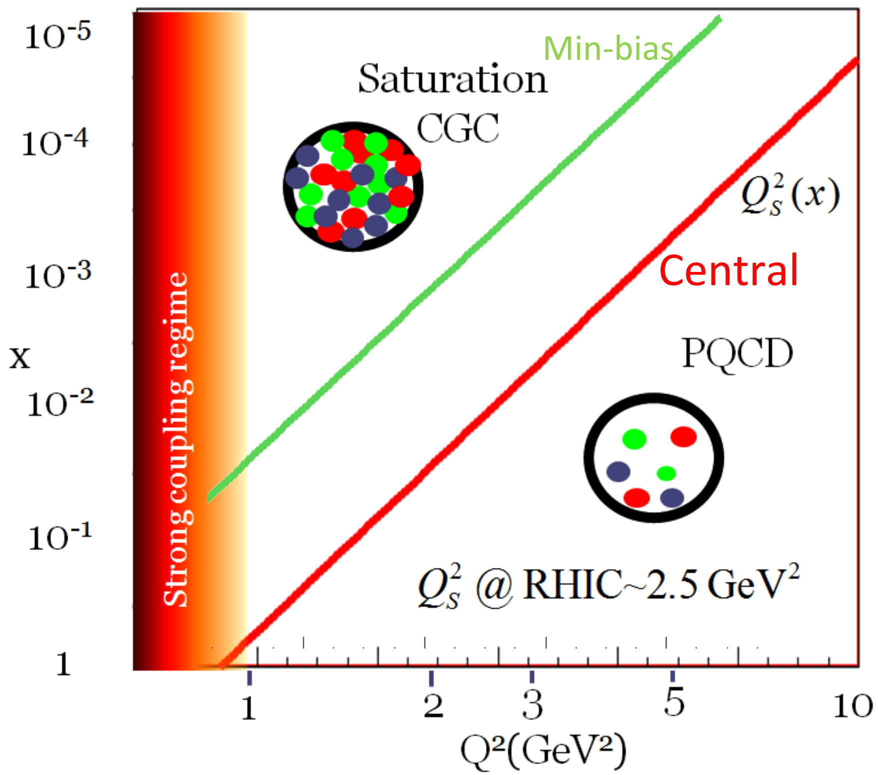
Ratio Nuclear nPDF to proton PDF*A

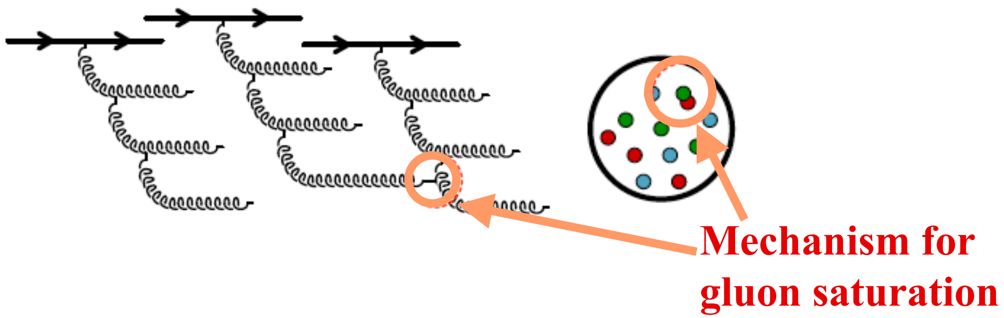
$$R_G^{Pb}(x,Q^2) = \frac{xG_A(x,Q^2)}{AxG_p(x,Q^2)}$$



e.g. EPS09NLO nPDFs: Eskola , Paukkunen, Salgado, JHP04 (2009)065

The Color Glass Condensate





- High density @ low-x leads to recombination of gluons, hence suppression.
- Characterized by Saturation scale Q_S

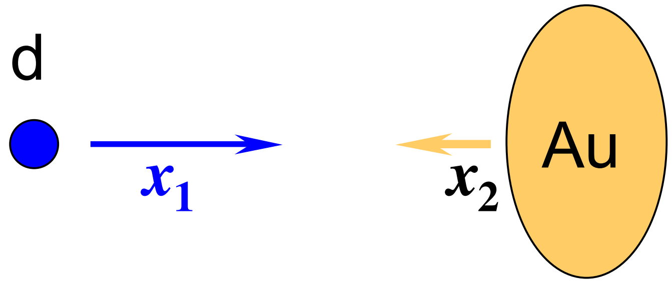
$$Q_S = Q_{0,S}\left(\frac{x_0}{x}\right)^{\lambda}$$

- Nuclear Amplification $xG_A = A^{1/3} xG_p$ (centrality dependence)
- Region of importance: low-x (forward rapidity)

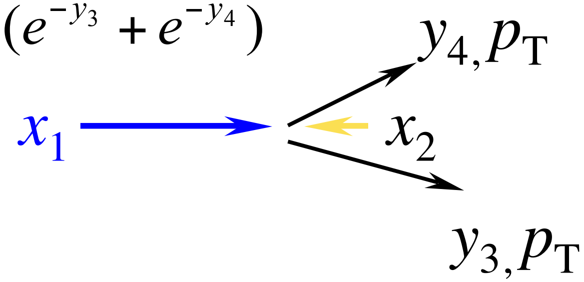
$$Q_S \propto A^{1/3} / x^{\lambda}$$

See e.g., F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan, arXiv:1002.0333

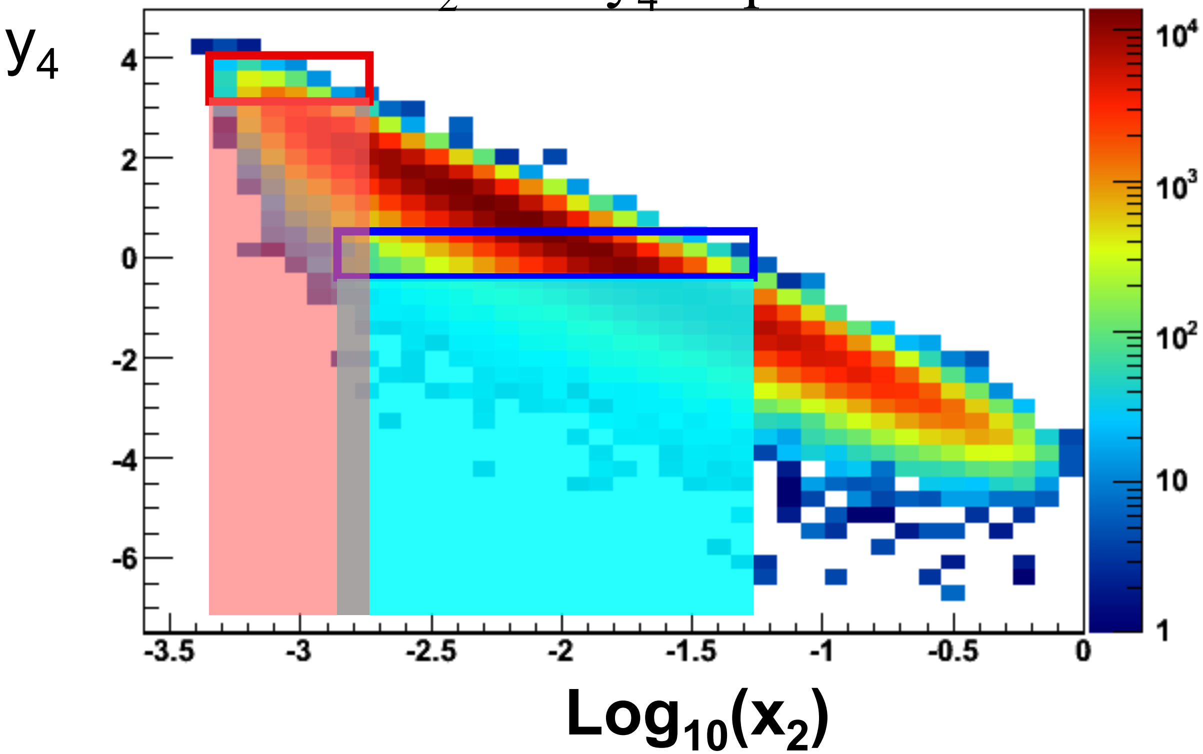
Parton kinematics in 2->2 process



$$x_{Au} = \frac{p_T}{\sqrt{s}}(e^{-y_3} + e^{-y_4})$$



Example: Require Parton 3 in Forward direction $3<y_3<4$ gives variation of x_2 with y_4 of parton 4



Select y of parton 4:

Mid-rapidity y_4~0

Mid-Fwd: $x_2 \sim 10^{-2}$

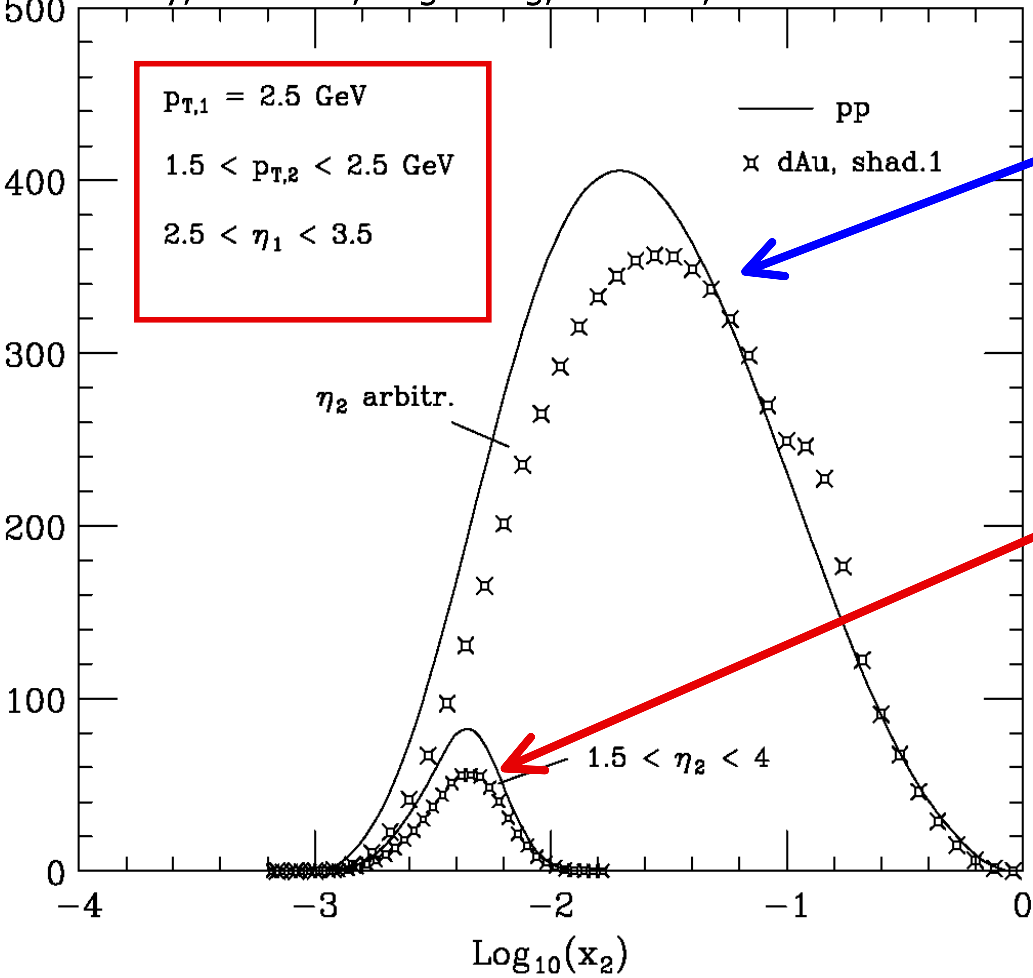
Forward y_4~3:

Fwd-Fwd $x_2 \sim 10^{-3}$

Decrease x_2 with decreasing p_T

Singles vs. di-Hadrons

Guzey, Strikman, Vogelsang, PL B603, 173



Forward Single Hadrons

p_T=2.5 2.5<η<3.5

Forward di-Hadrons

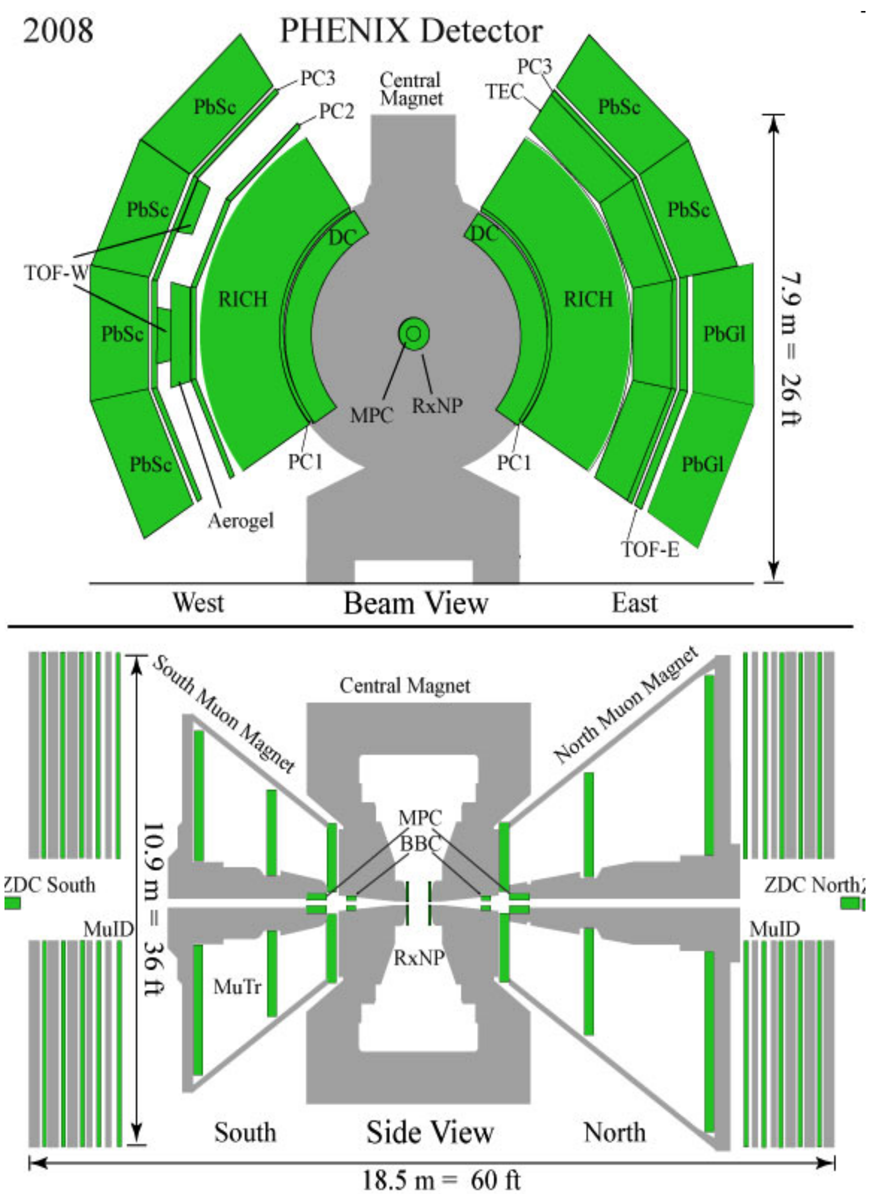
Probe:

→Narrower x-range

→Smaller mean x_2

PHENIX Detector at RHIC

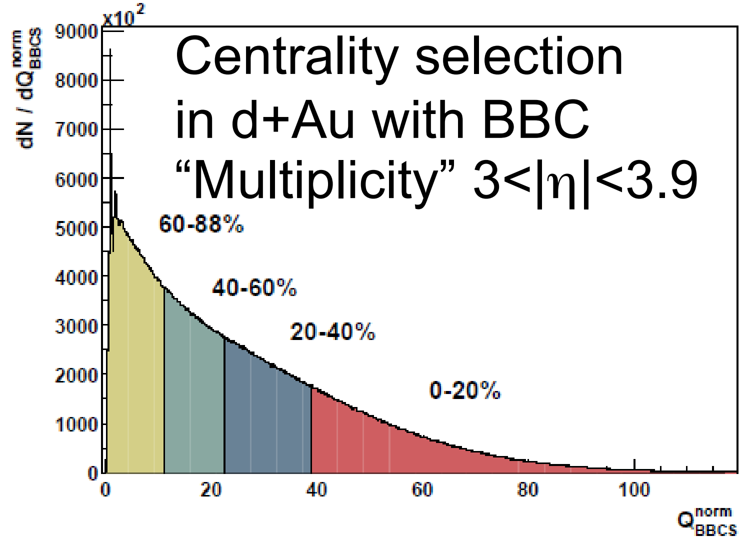
PHENIX



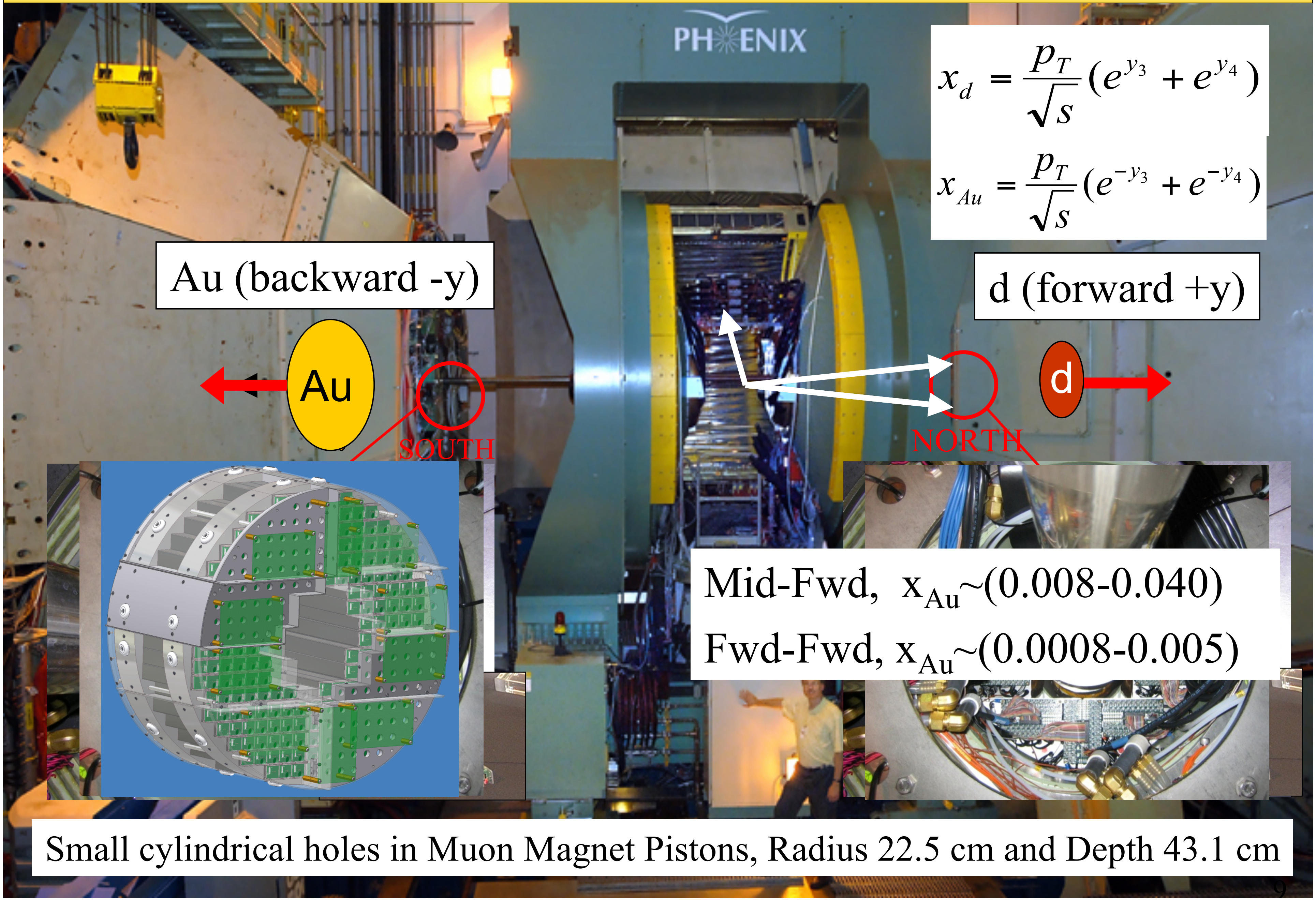
For this presentation:

d+Au at 200 GeV

- Central Arms |η| <0.35:
  - π^0's in EM Calorimeters
  - Hadrons (tracking)
- Muon Arms
  - π^0's in Muon Piston Calorimeter
- Beam-Beam Counters



PHENIX Muon Piston Calorimeter



$$x_d = \frac{p_T}{\sqrt{s}}(e^{y_3} + e^{y_4})$$

$$x_{Au} = \frac{p_T}{\sqrt{s}}(e^{-y_3} + e^{-y_4})$$

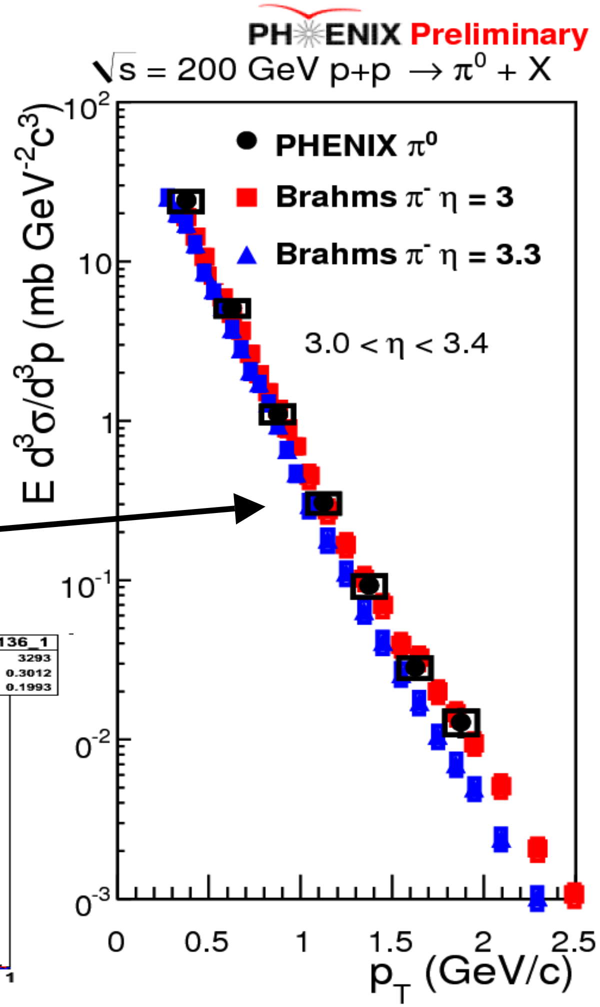
Mid-Fwd, x_{Au}~(0.008-0.040)

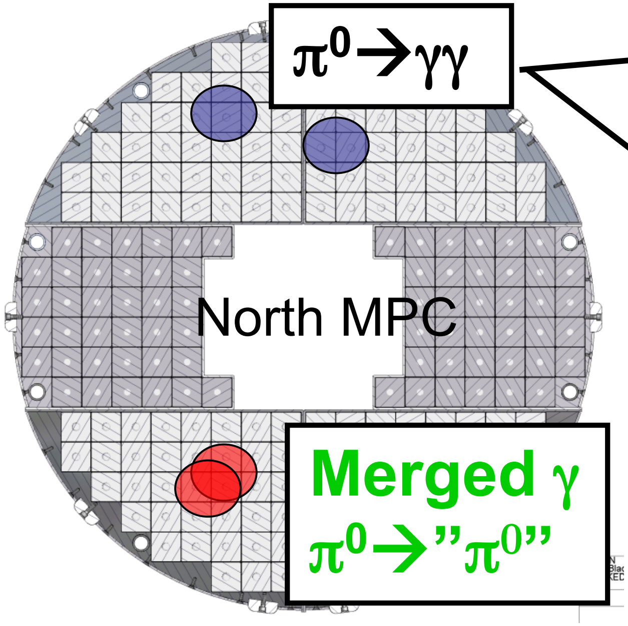
Fwd-Fwd, x_{Au}~(0.0008-0.005)

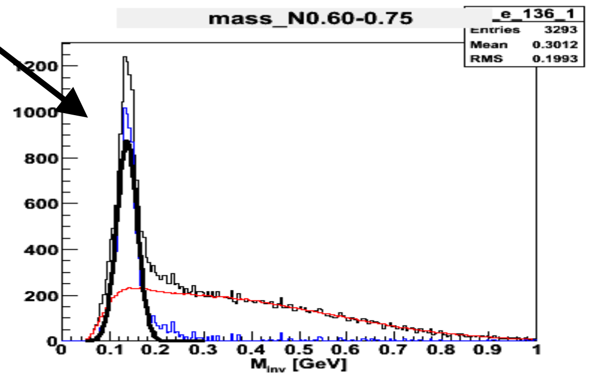
Small cylindrical holes in Muon Magnet Pistons, Radius 22.5 cm and Depth 43.1 cm

MPC Particle Identification

- ID π^0 up to E ~ 25 GeV with MPC 3.1< |η| < 3.9
  - Limitations: tower separation and merging effects
  - **Use π^0s for 7 GeV < E < 22 GeV -> p_T max ~ 2 GeV/c**
  - η' s to high p_T
- Single Clusters for E > 15 GeV
  - **Dominated by π^0 (~ 80%) -> Access higher p_T**
- Good agreement between PHENIX MPC π^0 and BRAHMS π^- at η~3.2 for p+p at 200 GeV





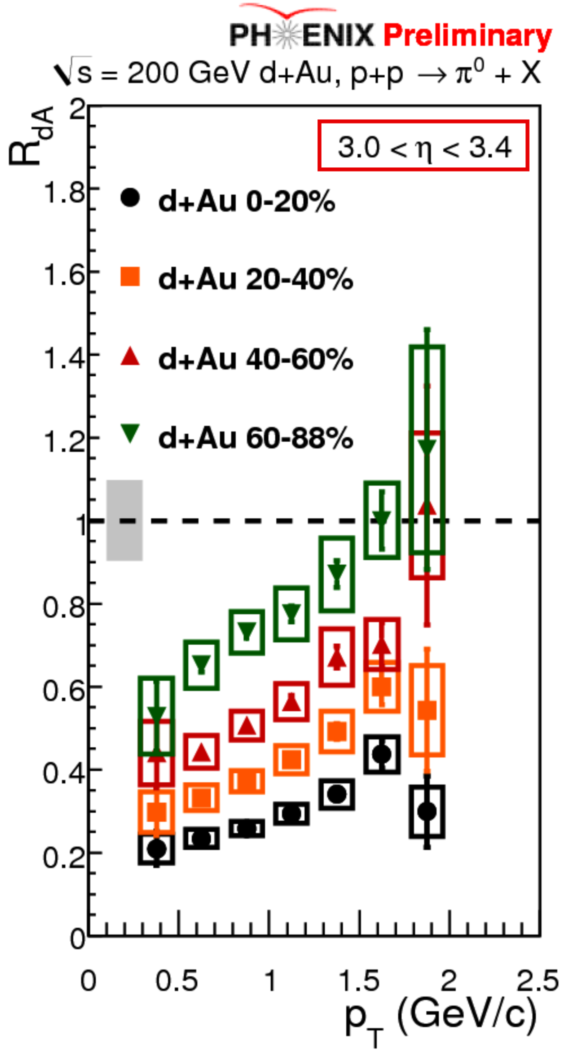


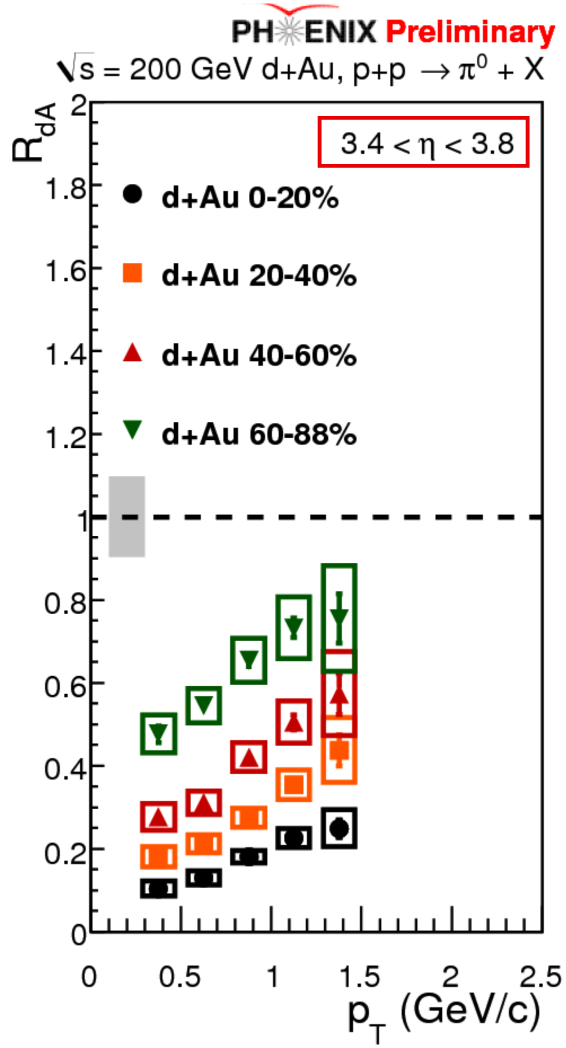
π^0 R_{dA}: Centrality, Rapidity Dependence

- R_{dAu} with π^0 in MPC

$$R_{dAu} \equiv \frac{1}{\langle N_{coll} \rangle} \frac{d^2N^{d+Au}/dp_T d\eta}{d^2N^{p+p}_{inel}/dp_T d\eta}$$

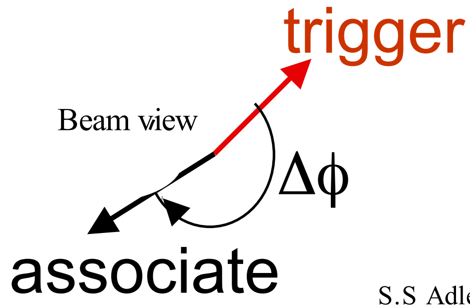
- **Suppression increases with:**
  - Increasing centrality
  - Increasing rapidity
  - Decreasing p_T
- I.e., with decreasing x_{Au} or increasing thickness.
- More detail with correlation studies.



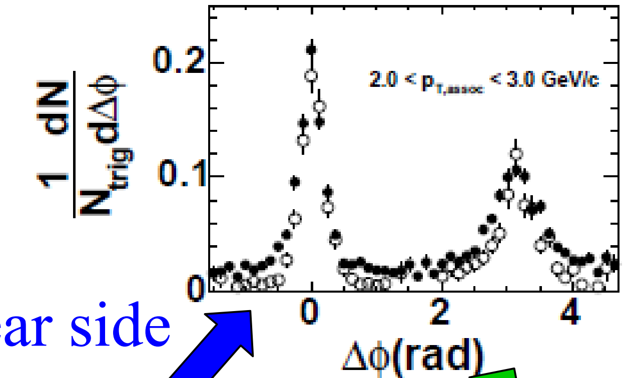


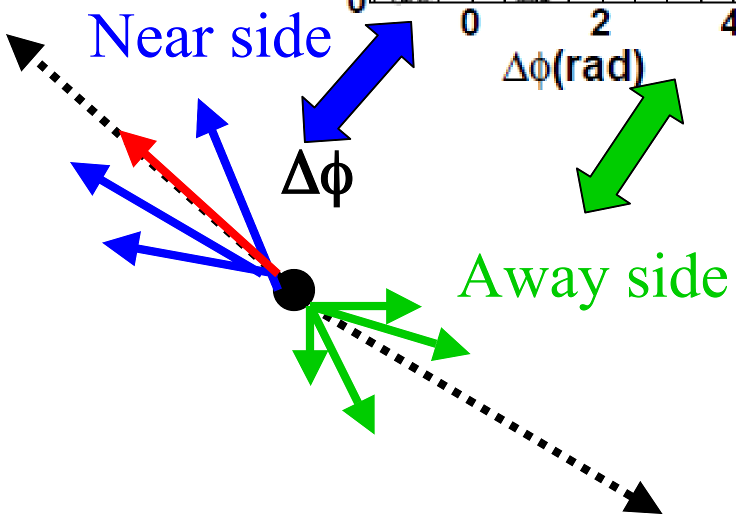
di-Hadron (di_Jet) Δφ Correlations

- Measure Δφ of all particle pairs
  - **Trigger particle** (usually leading p_T)
  - **Associate particle** (lower p_T)
    - *Near side Associate particles*
    - *Away side Associate particles*



S.S Adler et al, Phys. Rev. C 73:054903,2006.





"Conditional Yield"

$$CY = \frac{N_{pair}}{N_{trig}\varepsilon_{assoc}} = \frac{1}{N_{trig}}\int \frac{dN^{assoc}}{d\Delta\phi} d\Delta\phi$$

Number of correlated particle pairs per trigger particle after corrections for efficiencies, PID background, and subtracting uncorrelated background.

Pair Nuclear Modification Factor: J_{dA}

We define the di-Hadron or "Pair Nuclear Modification factor" J_{dA}

$$J_{dA} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{dA}^{pair} / \sigma_{dA}}{\sigma_{pp}^{pair} / \sigma_{pp}}$$

Completely analogous to the Hadron Singles "Nuclear Modification factor" R_{dA}

$$R_{dA} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{dA}^{sgl} / \sigma_{dA}}{\sigma_{pp}^{sgl} / \sigma_{pp}}$$

One can show $J_{dA} = I_{dA}^{trig} \times R_{dA}^{trig}$ where $I_{dA} = \frac{CY_{dA}}{CY_{pp}}$

For di-Hadron studies, I_{dA} has been used most frequently.

- Indicators of nuclear effects with pair measurements:
  - $J_{dA} < 1$, just as with $R_{dA} < 1$
  - Angular broadening of correlation width - new feature

An Aside: The problem with I_{dA}

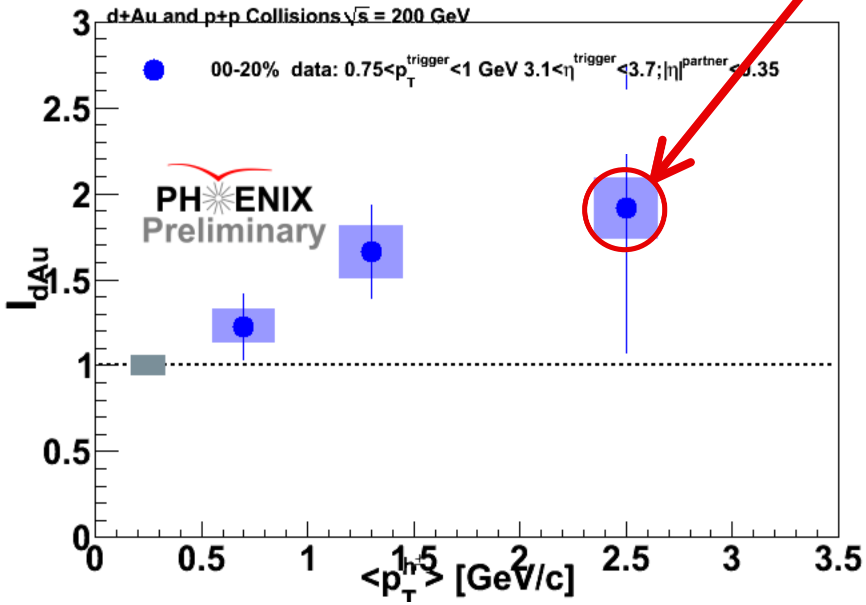
While the pair Yield, and J_{dA}, are independent of the trigger/associate particle label, the CY and I_{dA} do depend on the label.

$$\boxed{I_{dA}^{fwd,trig} \neq I_{dA}^{mid,trig}}$$

$$I_{dA}^{fwd,trig} = J_{dA} / R_{dA}^{fwd} \qquad I_{dA}^{mid,trig} = J_{dA} / R_{dA}^{mid}$$

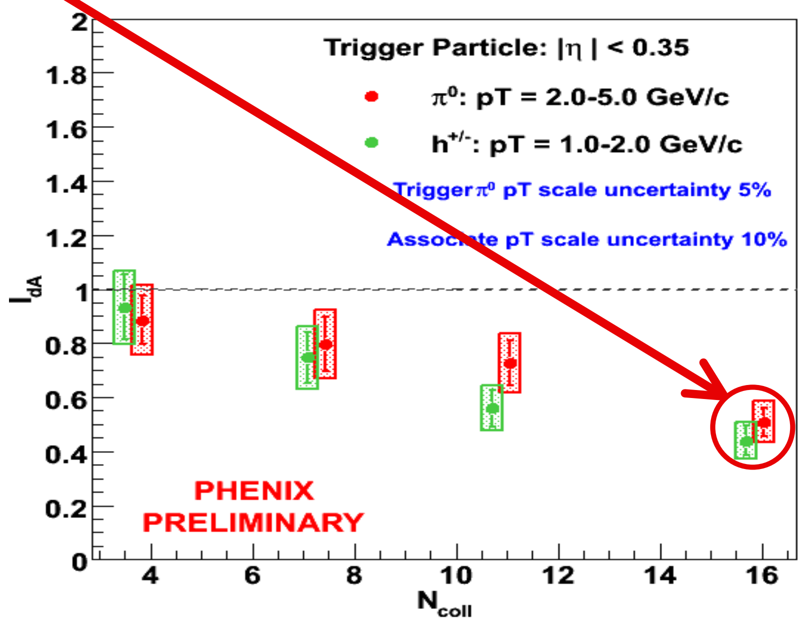
Same pair Yield, J_{dA}

I_{dA} Fwd-rapidity trigger



I_{dA} Mid-rapidity trigger

Associate π^0: $3.1 < \eta < 3.9$, pT = 0.45-1.59 GeV/c



Mid-Forward di-Jets with $\Delta\eta \sim 3.4$

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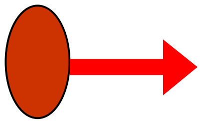
For p+p: $x_2 \sim 10^{-2}$

(d+Au $A^{1/3}$ effect)



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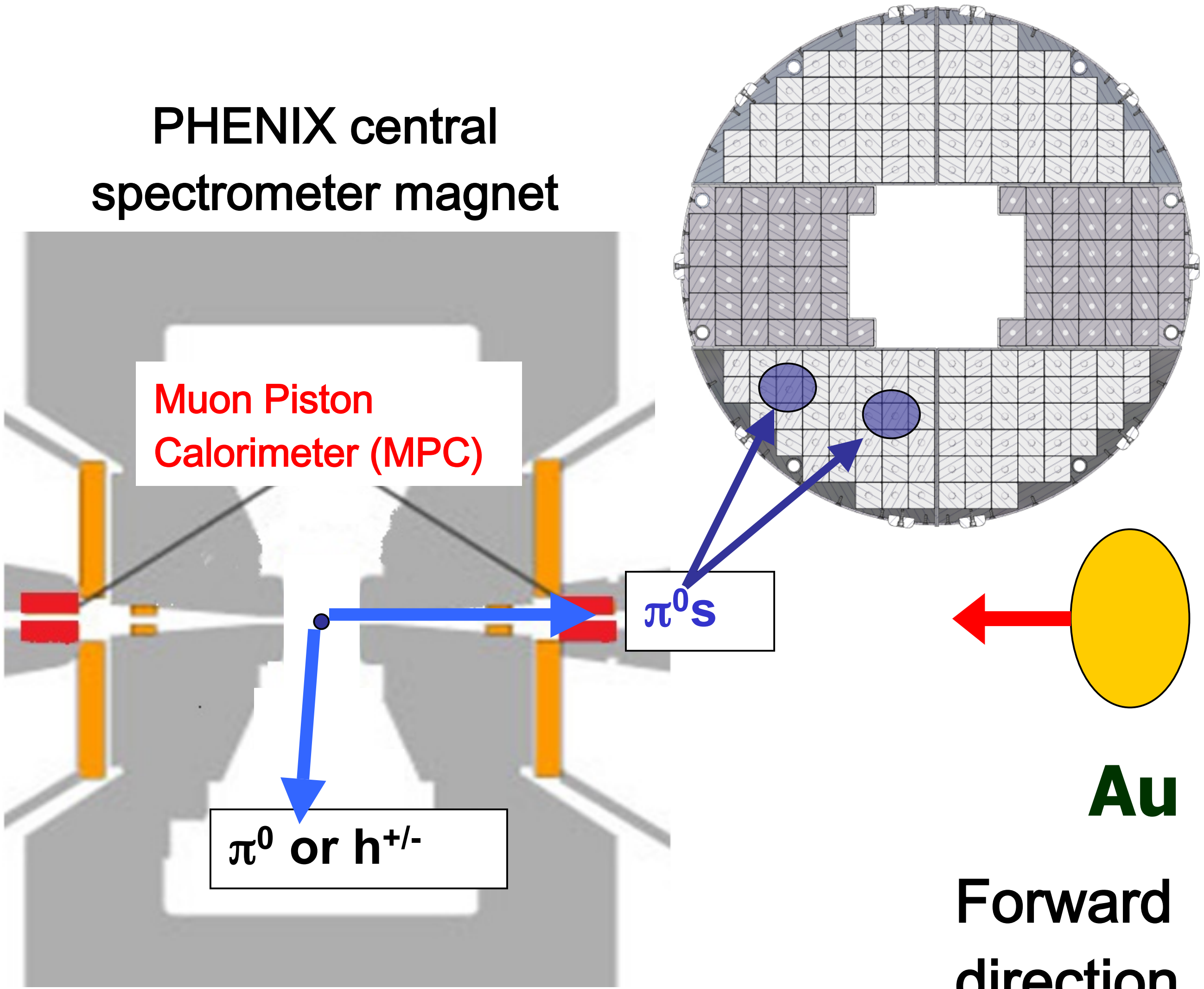
PHENIX central spectrometer magnet



Side View

Au

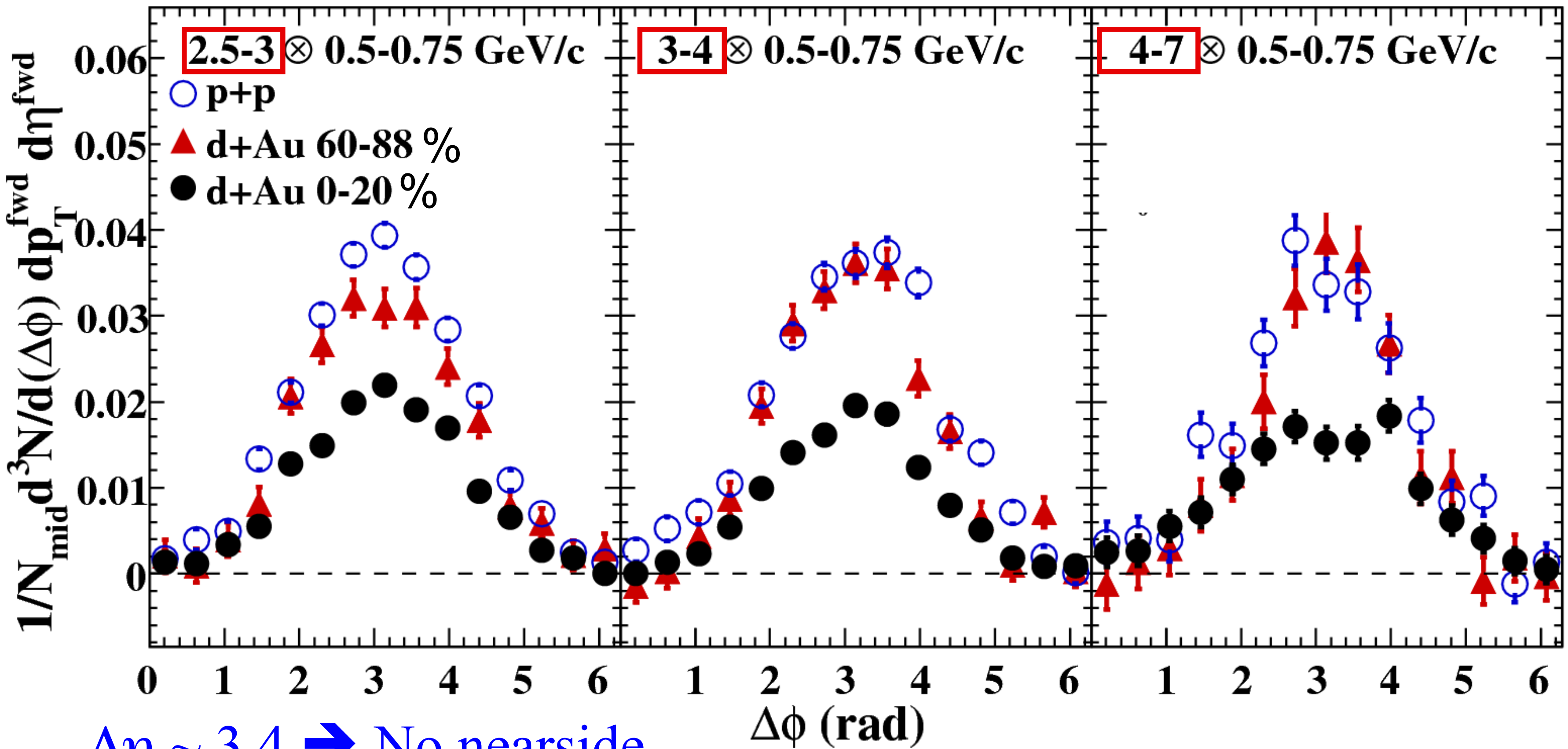
Backward direction (South) ←

Forward direction (North) →

Mid-Forward Per-Trigger Correlations

- Mid-Forward π^0–π^0 Correlations; Mid-rapidity triggered
  - Central d+Au shows suppression
  - No broadening apparent

$|\eta^{mid}| < 0.35$, $\eta^{fwd} = 3.0\text{-}3.8$



$\Delta\eta \sim 3.4$ ➔ No nearside

Mid-Fwd J_{dAu} vs N_{coll}, p_T^{mid}, p_T^{fwd}

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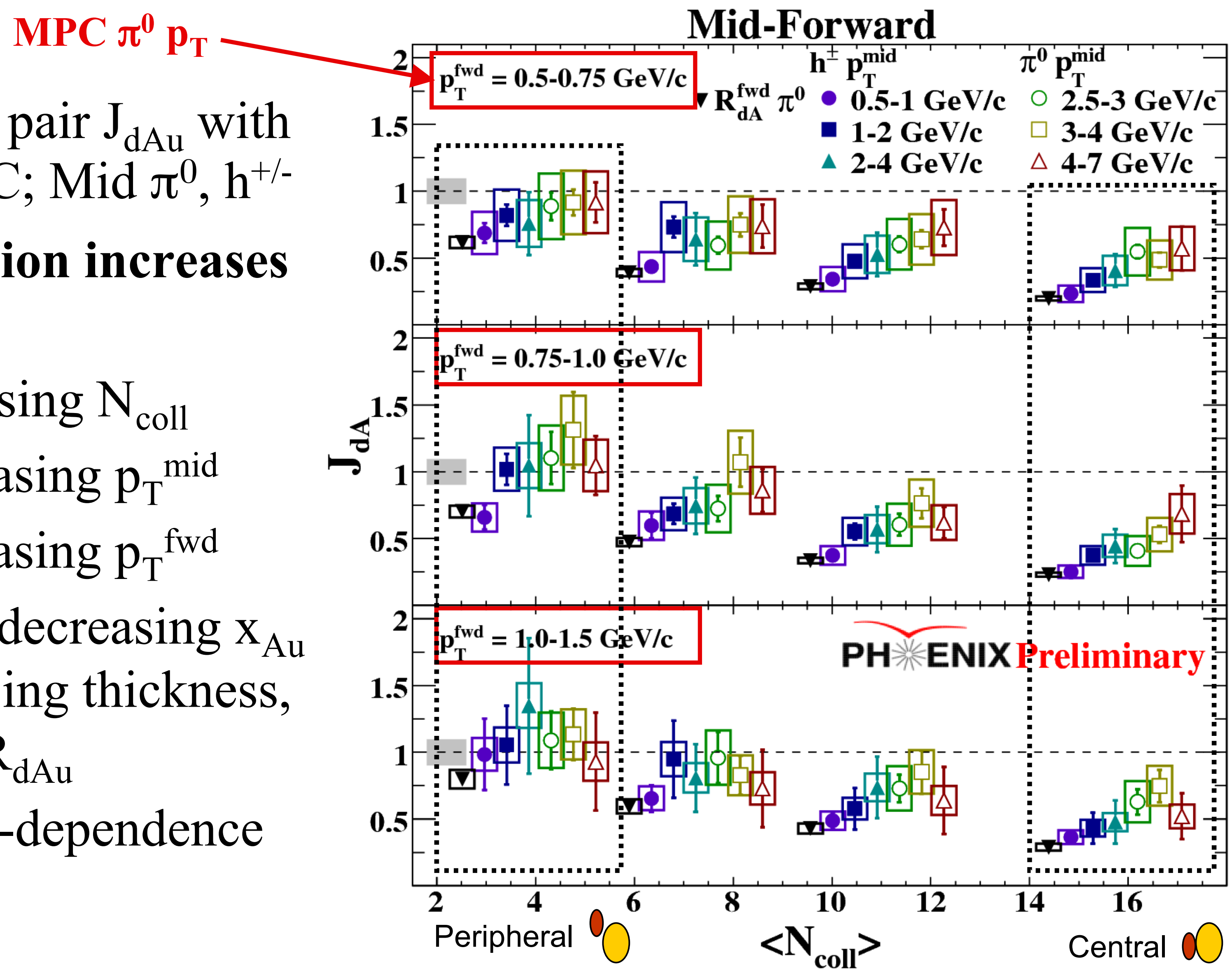
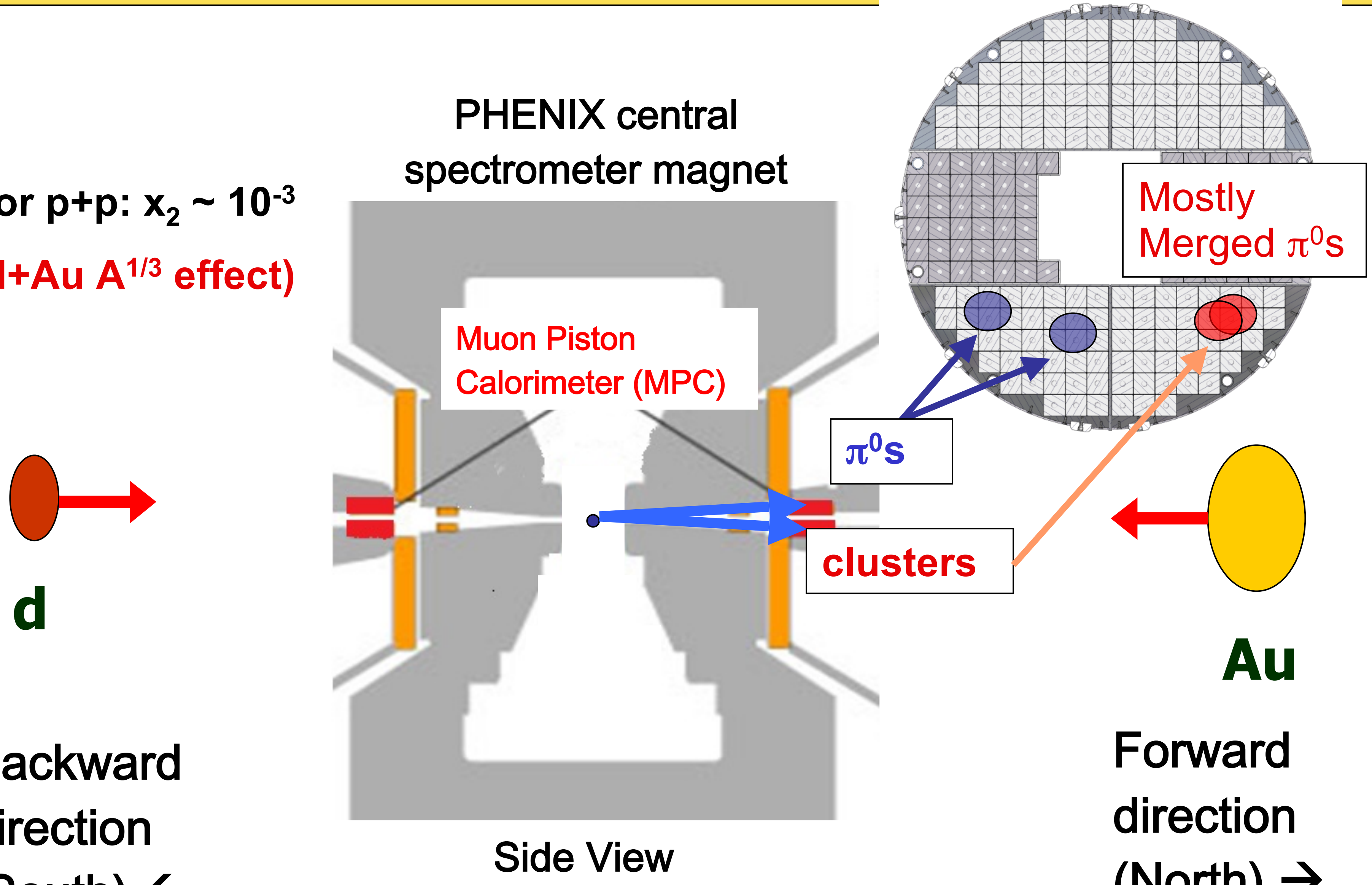
- Mid-Fwd pair J_{dAu} with π^0 in MPC; Mid π^0, $h^{+/-}$
- **Suppression increases with:**
  - Increasing N_{coll}
  - Decreasing p_T^{mid}
  - Decreasing p_T^{fwd}
- I.e., with decreasing x_{Au} or increasing thickness, just like R_{dAu}
- Look at y-dependence



Forward-Forward di-Jets at $\eta \sim 3.2$

For p+p: $x_2 \sim 10^{-3}$

(d+Au $A^{1/3}$ effect)



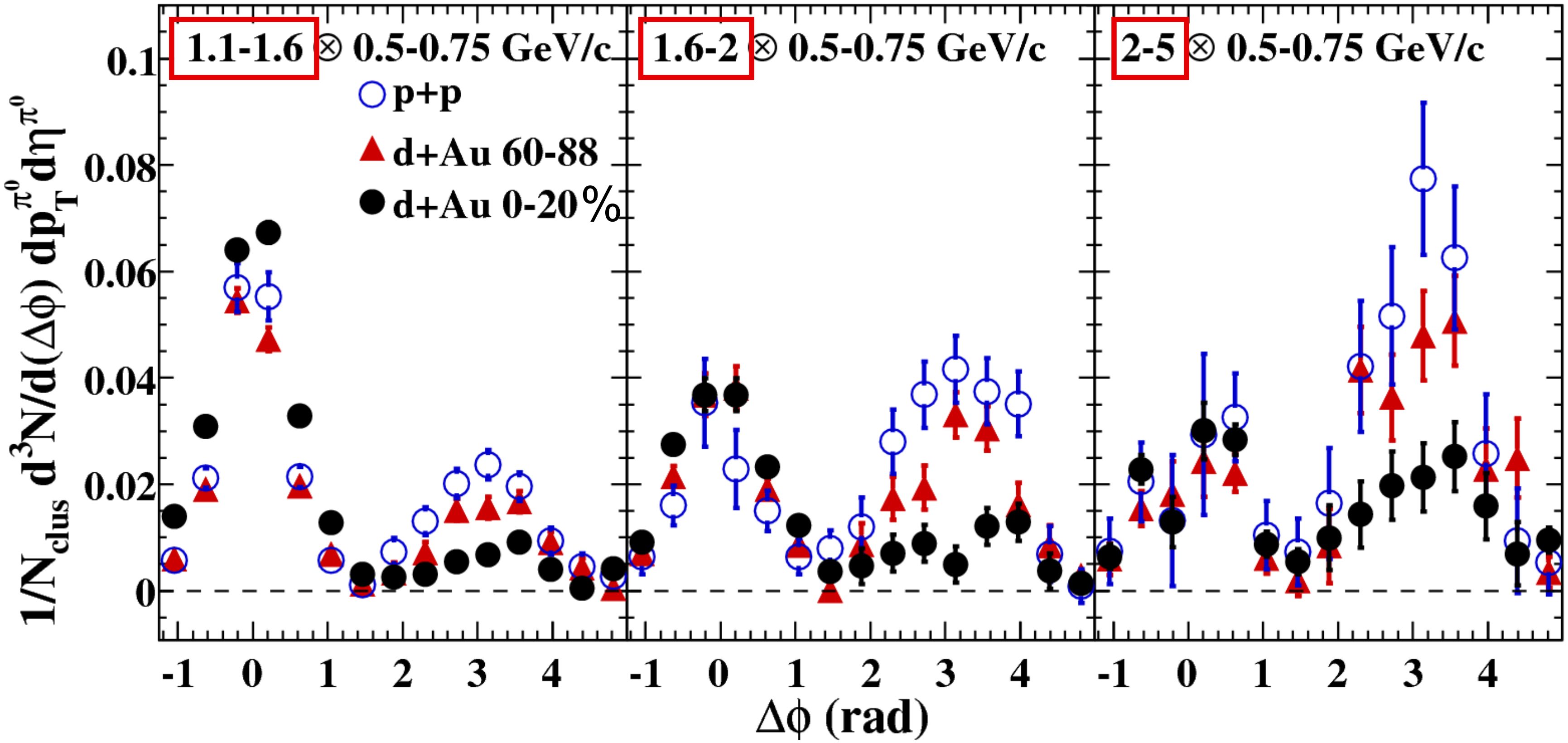
Backward direction (South) ←

Forward direction (North) →

Fwd-Fwd Per-Trigger Correlations

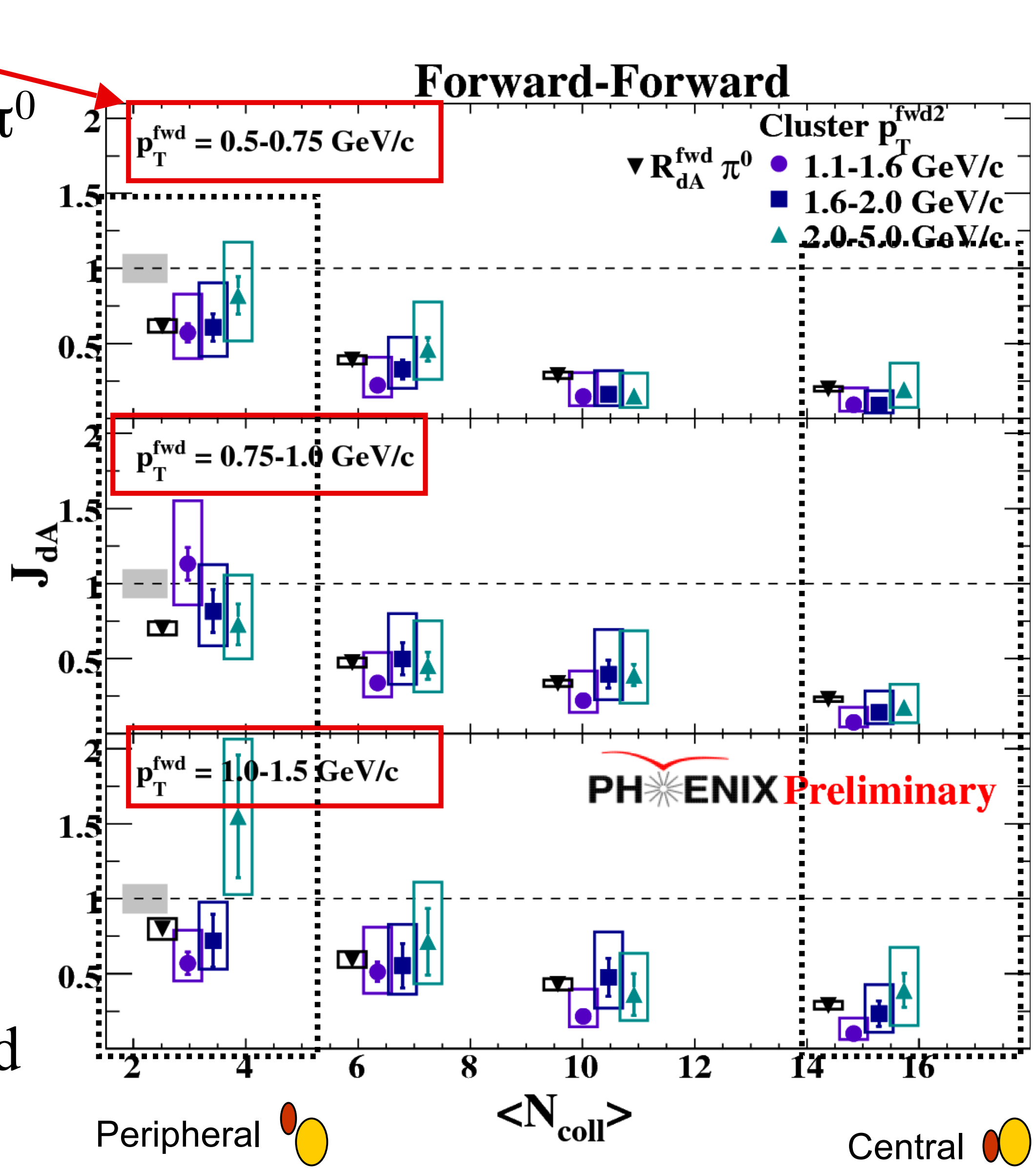
- Forward rapidity Cluster–π^0 Correlations
  - Use Zero-Yield at Minimum to subtract BG
  - Central d+Au shows significant suppression
  - Possible angular broadening in central d+Au

$\eta^{clus,\pi 0} = 3.0\text{-}3.8$



Fwd-Fwd J_{dAu} vs N_{coll}, p_T^{fwd1}, p_T^{fwd2}

- Fwd-Fwd pair J_{dAu} with π^0 and Cluster in MPC
- **Suppression increases with:**
  - Increasing N_{coll}
  - Decreasing p_T
  - Increasing y, i.e. "going forward"
- I.e., with decreasing x_{Au} or increasing thickness, just like R_{dAu}
- So, what has been learned beyond R_{dAu} ?

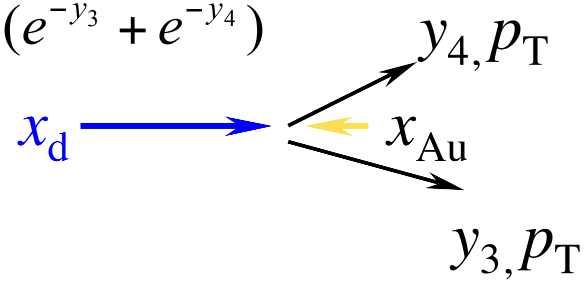


Systematize J_{dAu} Results

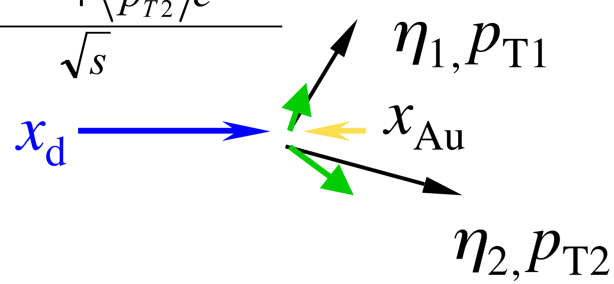
- The advantage of the pair measurement is that it constrains the kinematics.
- Estimate 2->2 parton kinematics ignoring fragmentation effects, i.e.
  - $\eta_1 \sim y_3$, $\eta_2 \sim y_4$ (not bad…)
  - $p_T = p_{T1}/z_1 = p_{T2}/z_2$: Set z=1
- Calculate $\langle x_{Au} \rangle$ estimate as if hadrons=partons using bin averages:

$$x_{Au}^{frag} \equiv \frac{\langle p_{T1} \rangle e^{-\langle \eta_1 \rangle} + \langle p_{T2} \rangle e^{-\langle \eta_2 \rangle}}{\sqrt{s}}$$

$$x_{Au} = \frac{p_T}{\sqrt{s}}\left(e^{-y_3} + e^{-y_4}\right)$$

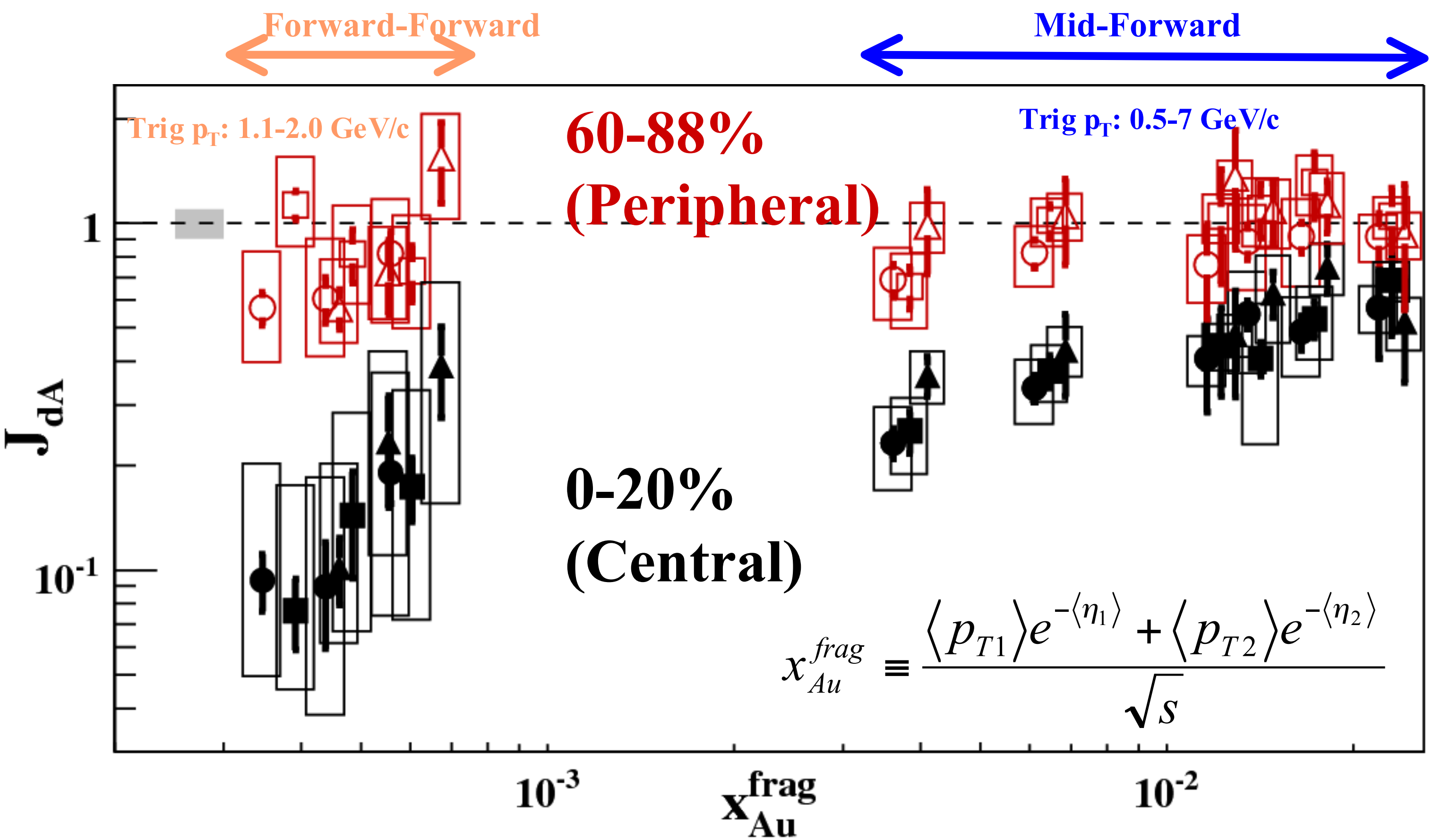


$$x_{Au}^{frag} \equiv \frac{\langle p_{T1} \rangle e^{-\langle \eta_1 \rangle} + \langle p_{T2} \rangle e^{-\langle \eta_2 \rangle}}{\sqrt{s}}$$



- Plot J_{dAu} vs. x^{frag} variable
  - Expect that x^{frag} underestimates x_{Au}
  - But if $\langle z \rangle \sim$constant then x^{frag} will be roughly proportional to $\langle x_{Au} \rangle$

x_{Au}^{frag} Dependence of J_{dAu}

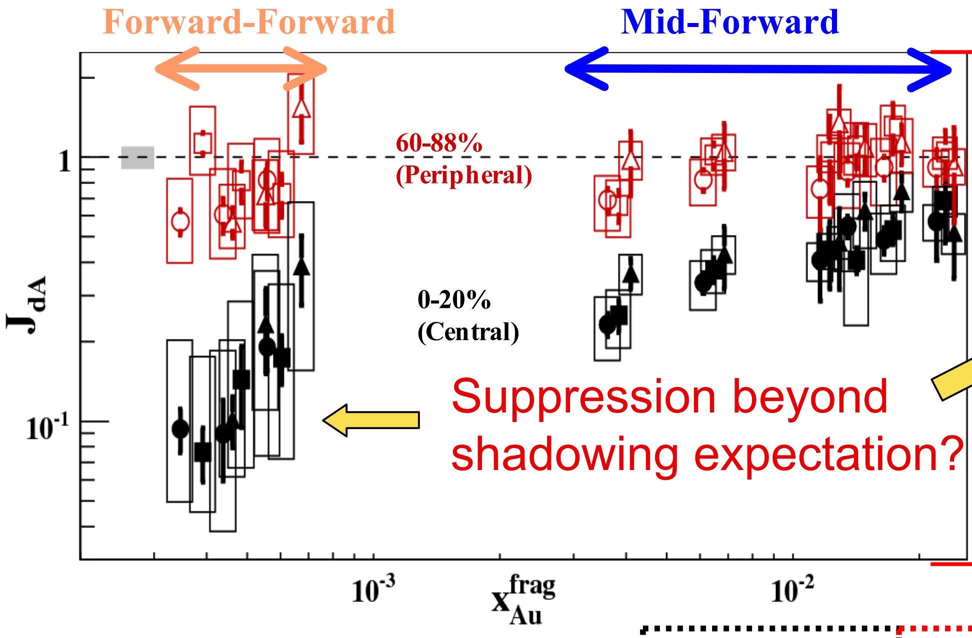


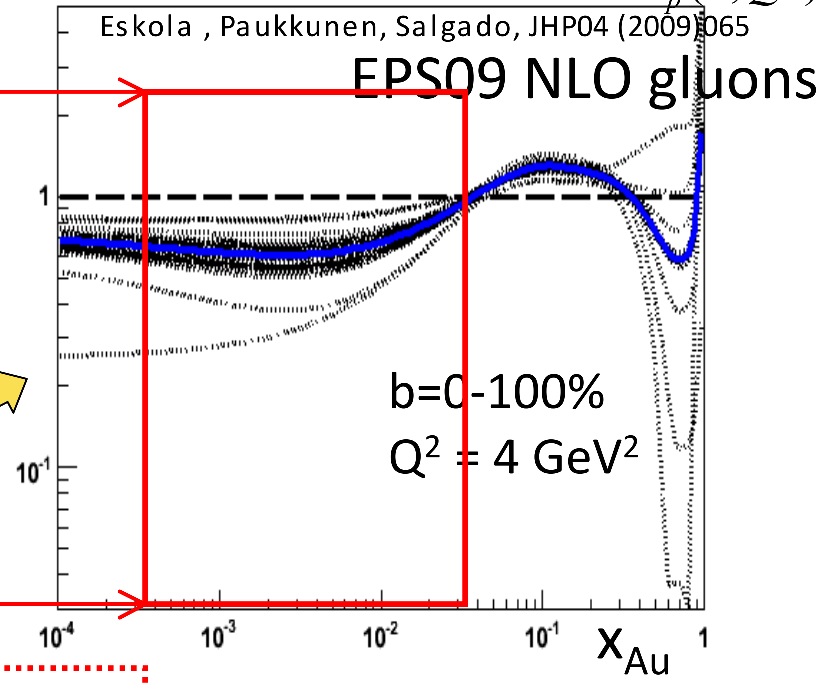
- Results show systematic dependence of J_{dAu} over large x_{Au} range.
  - No suppression for peripheral d+Au
  - Suppression for central d+Au increases strongly with x_{Au}^{frag}
- Interpretation? Indicates very strong shadowing effect. CGC?

Note: points for mid-fwd JdA are offset for visual clarity

Large Shadowing effect

$$R_G^{Au}(x,Q^2) = \frac{xG_{Au}(x,Q^2)}{AxG_p(x,Q^2)}$$





$$J_{dA} = \frac{\sigma_{dAu}^{pairs}/\sigma_{dAu}}{\langle N_{coll}\rangle \sigma_{pp}^{pairs}/\sigma_{pp}} \propto \frac{f_d^a(x_d) \otimes f_{Au}^b(x_{Au}) \otimes \hat{\sigma}^{ab\to cd} \otimes D(z_c, z_d)}{f_p^a(x_p) \otimes f_p^b(x_p) \otimes \hat{\sigma}^{ab\to cd} \otimes D(z_c, z_d)}$$

High x, mostly quarks
Weak effects expected

Low x, mostly gluons → J_{dA} ~measures R_G^{Au}

Summary

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- The observed suppression of hadron yields at forward rapidity in d+Au collisions at RHIC has confirmed interesting cold nuclear matter effects at small x.
- Di-Hadron correlation measurements allow to further investigate the suppression with better constraints on the kinematics (fix range of relevant x values).
- Di-Hadron correlations at forward rapidity probe very low x values and indicate very large suppression.
  - New input to nPDFs? Perhaps confirming Color Glass Condensate picture of Gluon Saturation?
- In order to understand the results in Pb+Pb collisions at the LHC, it will be essential to understand the cold nuclear matter effects which may be large.
  - At fixed p_T - mid-rapidity at the LHC probes the same x-region as forward at RHIC where we see strong cold nuclear matter effects.

PHENIX

EXTRAS

π^0 (trigger,central)/π^0 (associate,forward)

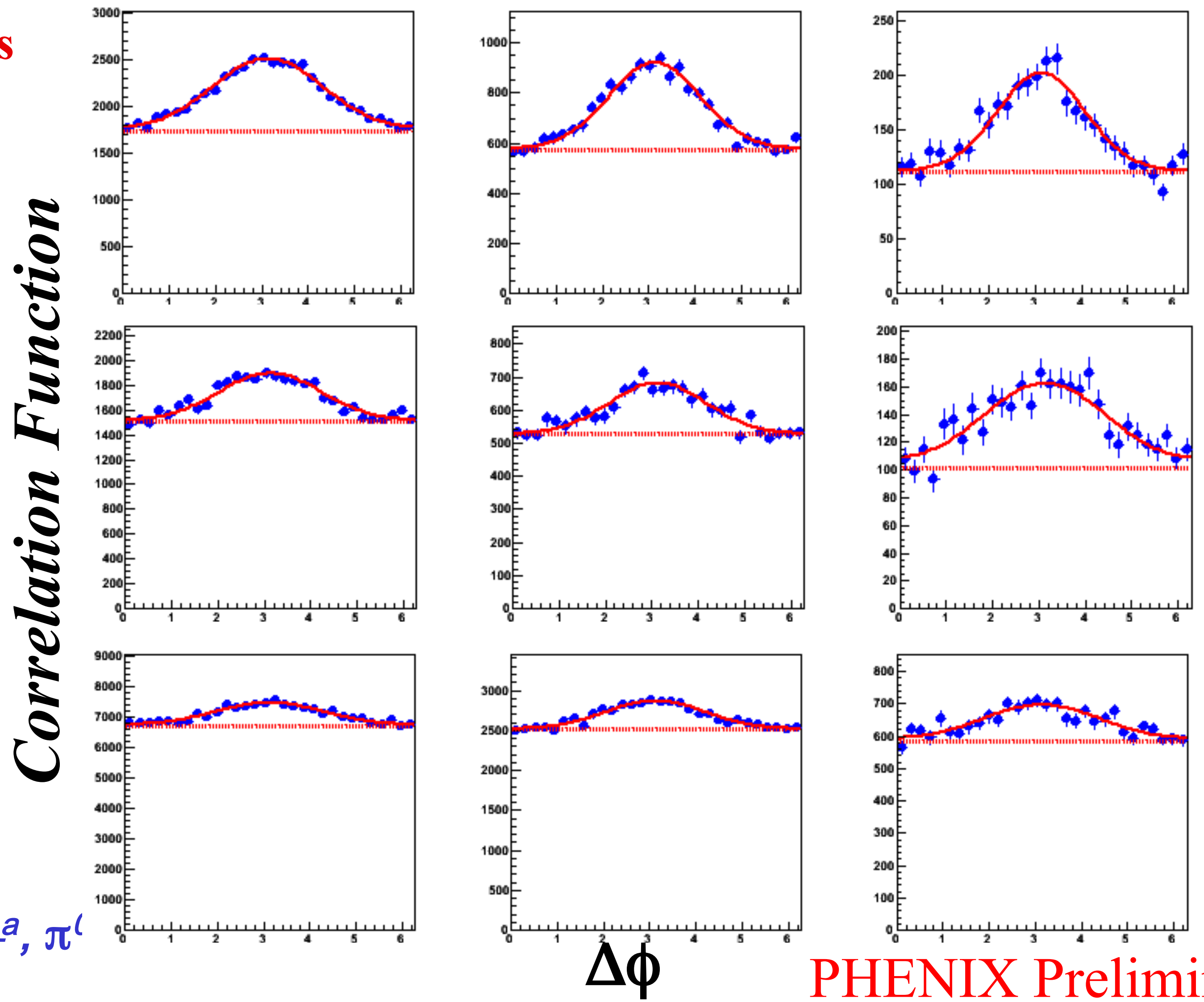
$3.0 < p_T^t < 5.0$ GeV/c for all plots

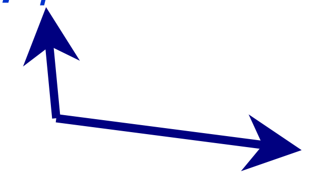
$<p_T^a>=0.55$ $<p_T^a>=0.77$ $<p_T^a>=1.00$

p+p

d+Au 60-88%

d+Au 0-20%





PHENIX Preliminary

Correlation Widths, d+Au and p+p

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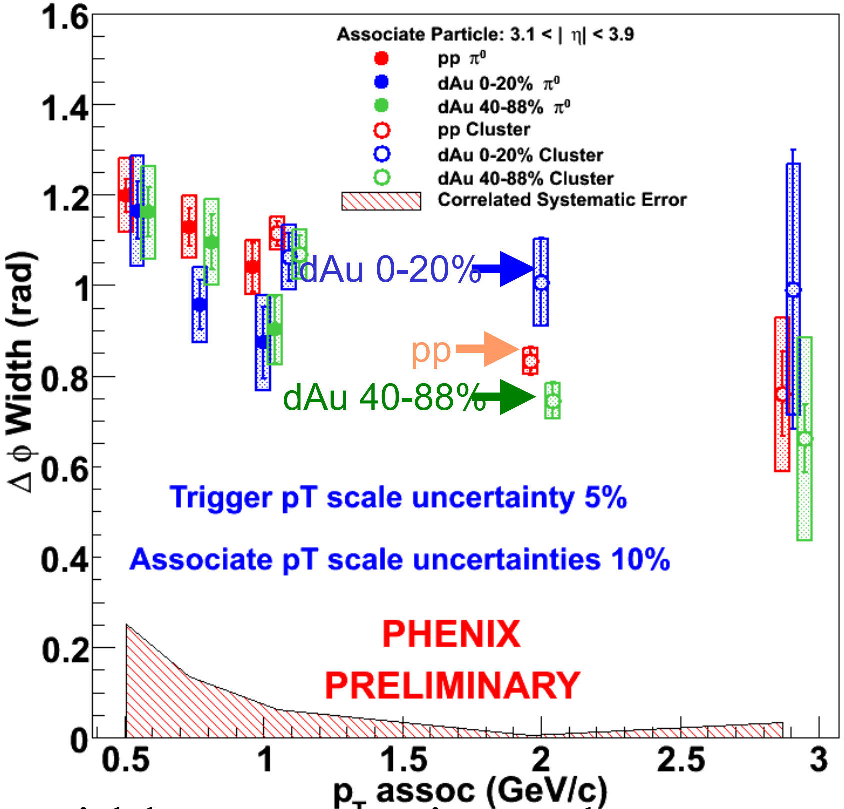
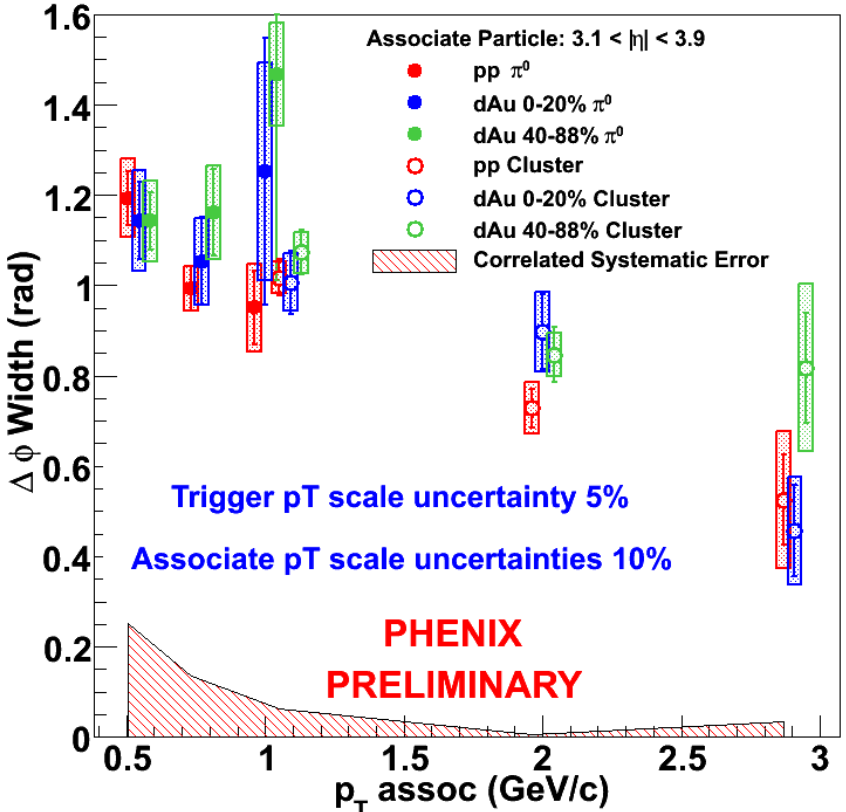
Trigger π^0: $|\eta| < 0.35$, $2.0 < p_T < 3.0$ GeV



Trigger π^0: $|\eta| < 0.35$, $3.0 < p_T < 5.0$ GeV



- Widths are consistent between p+p and d+Au (all centralities) within large statistical and systematic errors
- No broadening seen (within errors)

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